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Aflatouni et al.

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(54) **INTEGRATED LIGHT SOURCE
INDEPENDENT LINEWIDTH REDUCTION
OF LASERS USING ELECTRO-OPTICAL
FEEDBACK TECHNIQUES**

(58) **Field of Classification Search**
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USPC 385/3; 250/200, 201.1, 201.9;
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(71) Applicant: **California Institute of Technology,**
Pasadena, CA (US)

(72) Inventors: **Firooz Aflatouni,** Pasadena, CA (US);
Behrooz Abiri, Pasadena, CA (US);
Seyed Ali Hajimiri, La Canada, CA
(US)

(73) Assignee: **California Institute of Technology,**
Pasadena, CA (US)

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G02F 1/01 (2006.01)
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H01S 3/00 (2006.01)

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(2013.01); **H01S 3/005** (2013.01); **H01S 3/0085**
(2013.01); **H01S 2301/02** (2013.01)

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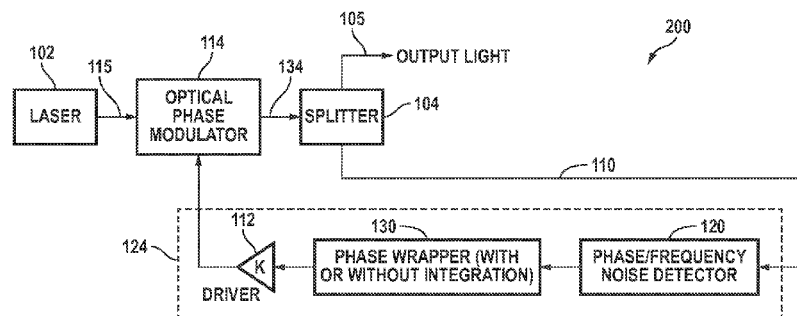
Primary Examiner — Ellen Kim

(74) *Attorney, Agent, or Firm* — Alston & Bird LLP

(57) **ABSTRACT**

An integrated optical linewidth reduction system includes a phase modulator adapted to modulate the phase of an incoming optical signal in response to a feedback control signal defined by a first electrical signal. The phase modulator is further adapted to generate a first optical signal travelling through a first optical path. The first electrical signal is representative of a phase noise of the first optical signal. An optical linewidth of the first optical signal is less than an optical linewidth of the incoming optical signal.

31 Claims, 5 Drawing Sheets



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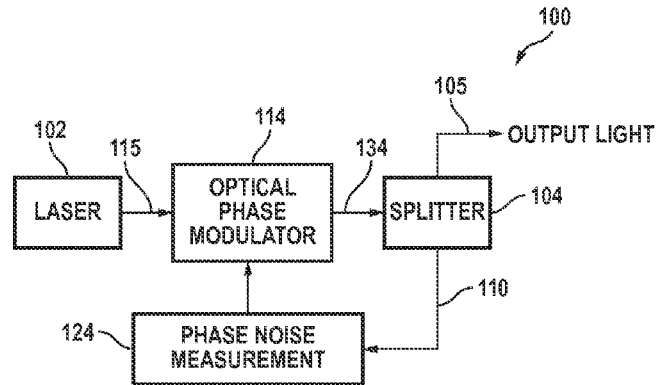


FIG. 1

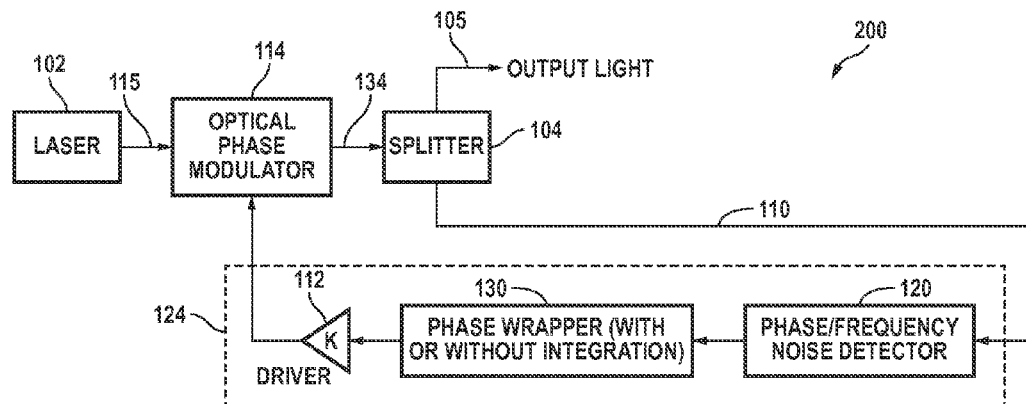


FIG. 2

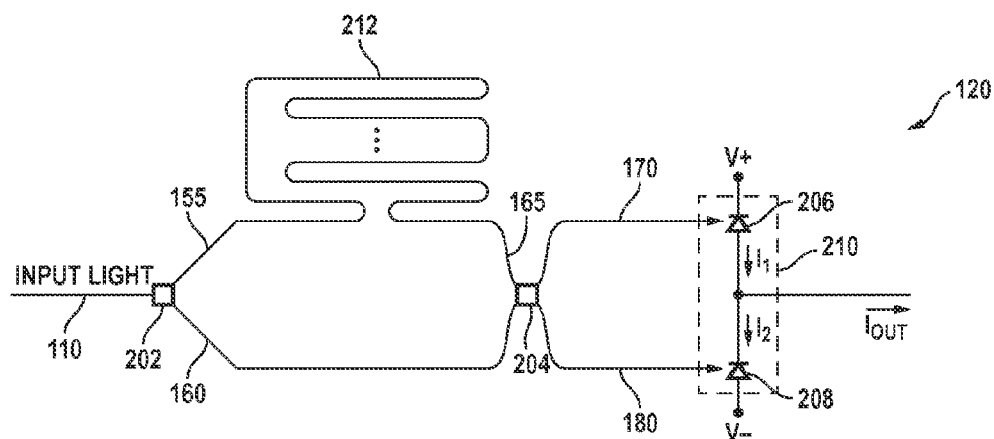


FIG. 3A

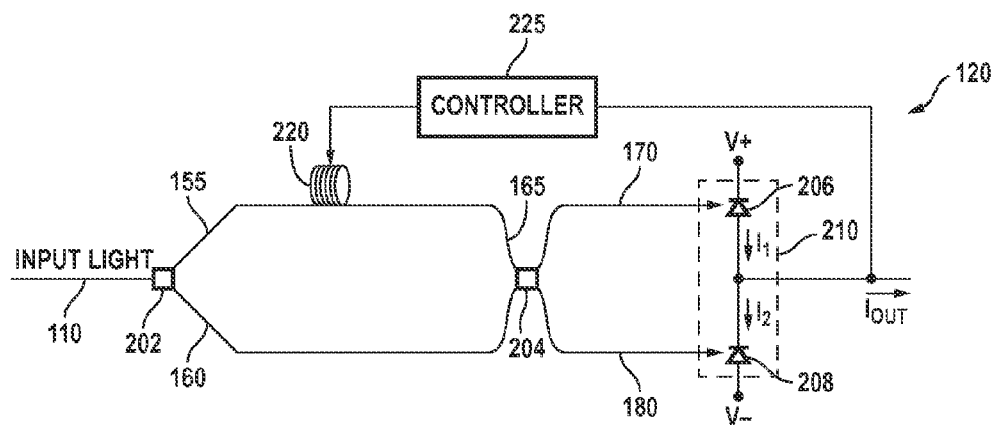


FIG. 3B

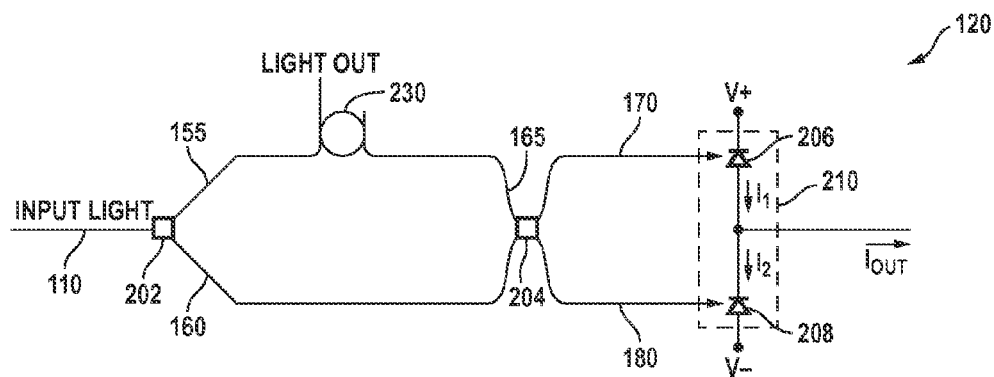


FIG. 3C

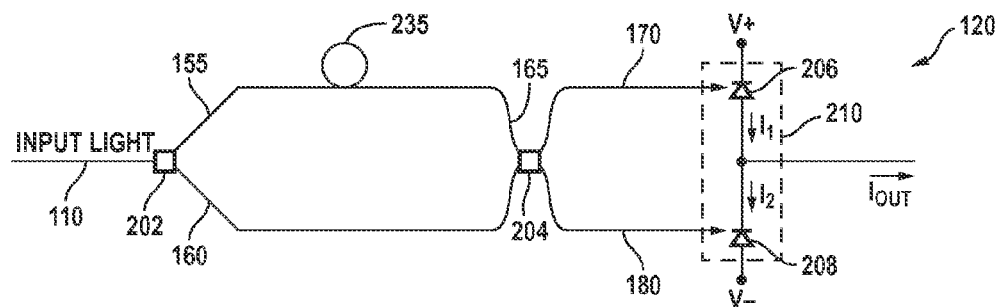


FIG. 3D

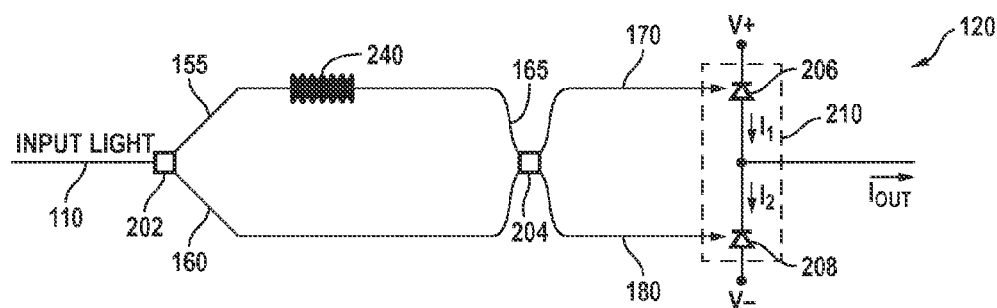


FIG. 3E

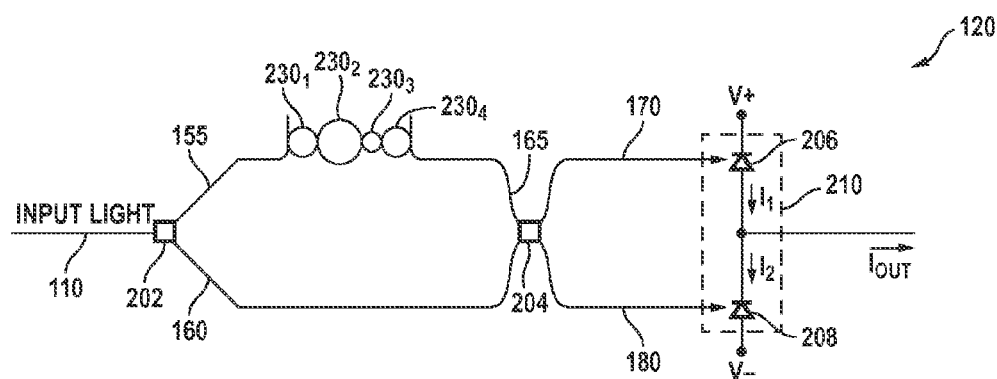


FIG. 3F

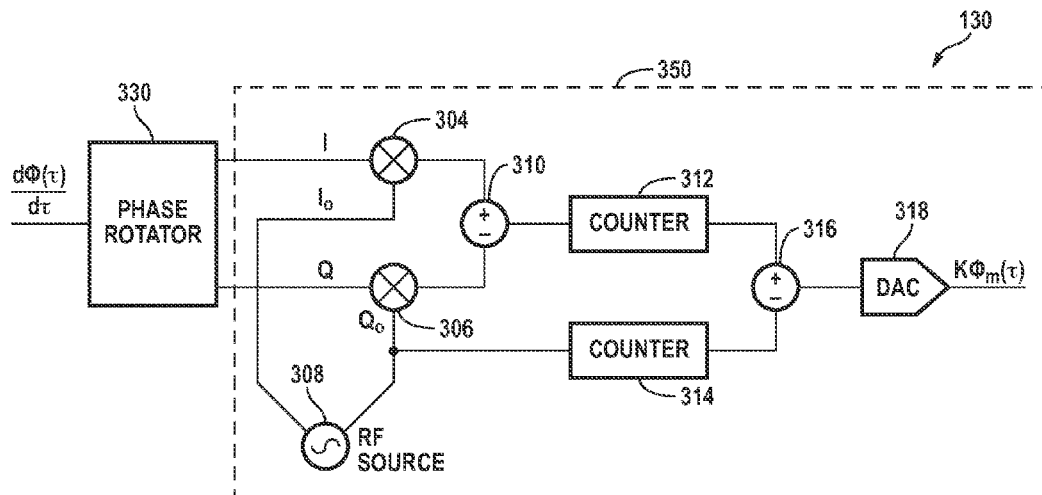


FIG. 4

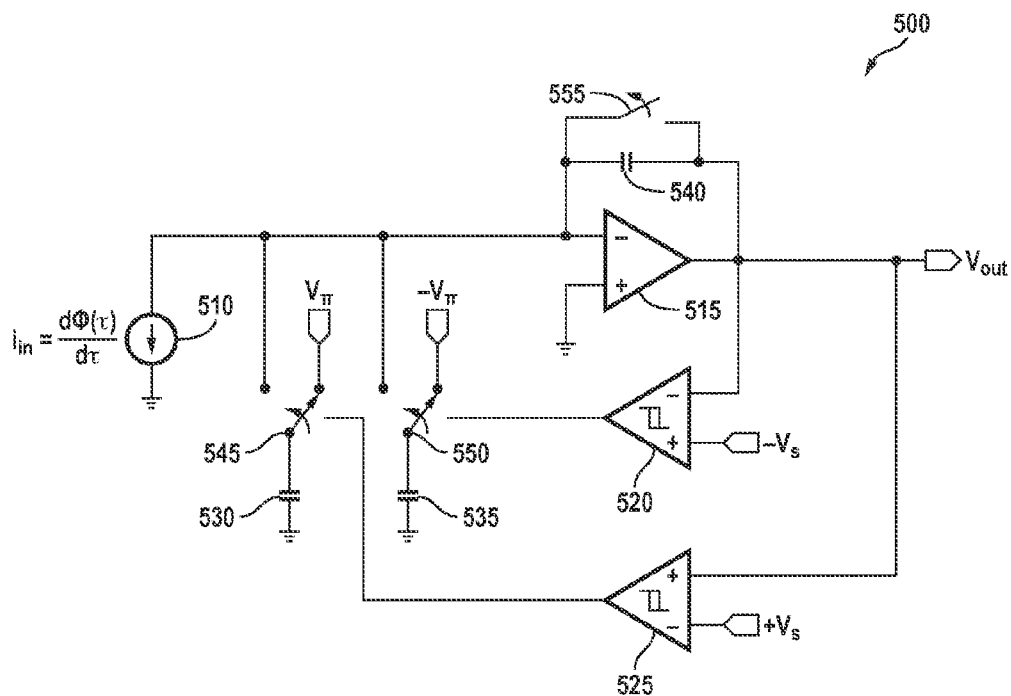


FIG. 5A

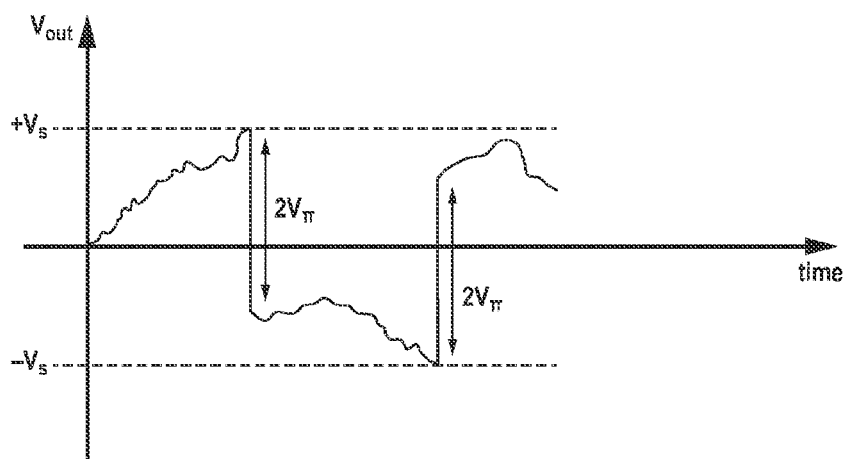


FIG. 5B

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INTEGRATED LIGHT SOURCE INDEPENDENT LINEWIDTH REDUCTION OF LASERS USING ELECTRO-OPTICAL FEEDBACK TECHNIQUES

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims benefit under 35 USC 119 (e) of U.S. Provisional Application No. 61/624,165, filed Apr. 13, 2012, entitled "Integrated Light Source Independent Linewidth Reduction of Lasers Using Electro-Optical Feedback Techniques", the content of which is incorporated herein by reference in its entirety. The present application is related to U.S. application Ser. No. 13/684,061, filed Nov. 21, 2012, entitled "Integrated Light Source Independent Linewidth Reduction of Lasers Using Feed-Forward Techniques", the content of which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

The present invention is related to optical signals, and more particularly to reducing a linewidth of an optical signal.

Compact lasers with narrow linewidth are known and used in applications such as coherent optical communication systems, portable and non-portable high resolution LIDAR systems, mm-wave and THz signal generation, optical imagers, optical phased arrays, sensing, opto-electronic oscillators, molecular and bio-molecular spectroscopy devices, and the like.

Commercially available Sub-KHz fiber laser linewidths have been achieved at the expense of weak tunability, large form factor, small wall-plug efficiency, and undesired mode hopping characteristic. Using a conventional feedback technique to cancel phase noise over a large frequency bandwidth often results in feedback loop instability because the laser is part of the feedback loop. Thus, the laser's characteristics such as its FM response may effect the loop performance such as the phase noise reduction bandwidth. Accordingly, a need continues to exist for an optical signal linewidth reduction system that overcomes the shortcomings of the conventional linewidth reduction systems.

BRIEF SUMMARY

According to one embodiment of the present invention, an integrated optical linewidth reduction system includes a phase modulator adapted to modulate the phase of an incoming optical signal in response to a feedback control signal defined by a first electrical signal. The phase modulator is further adapted to generate a first optical signal travelling through a first optical path. The first electrical signal is representative of a phase noise of the first optical signal. An optical linewidth of the first optical signal is less than an optical linewidth of the incoming optical signal.

According to one embodiment, the incoming optical signal is a laser beam. According to one embodiment, the integrated optical linewidth reduction system further includes a first splitter/coupler adapted to split the first optical signal into at least second and third optical signals travelling through second and third optical paths. The integrated optical linewidth reduction system further includes a second splitter/coupler adapted to split the third optical signal into at least fourth and fifth optical signals travelling through fourth and fifth optical paths. The fourth optical path has a longer propagation delay than the fifth optical path.

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A third splitter/coupler is adapted to generate a sixth optical signal by coupling a first portion of the fourth optical signal with a first portion of the fifth optical signal and deliver the sixth optical signal to a sixth optical path. The third splitter/coupler is further adapted to generate a seventh optical signal by coupling a second portion of the fourth optical signal with a second portion of the fifth optical signal and deliver the seventh optical signal to a seventh optical path. The integrated optical linewidth reduction system further includes a photo detection circuit comprising first and second photo detectors. The first photo detector is adapted to generate a second electrical signal in response to the sixth optical signal. The second photo detector is adapted to generate a third electrical signal in response to the seventh optical signal. The photo detection circuit supplies a fourth electrical signal in response to the second and third electrical signals. The fourth electrical signal is representative of a phase noise of the first optical signal.

According to one embodiment, the integrated optical linewidth reduction system further includes a true-time delay element disposed in the fourth optical path adapted to cause the longer propagation delay. According to one embodiment, the integrated optical linewidth reduction system further includes a resonator disposed in the fourth optical path adapted to cause the longer propagation delay. The integrated optical linewidth reduction system further includes a controller adapted to vary a delay associated with the resonator in accordance with a sample of the fourth electrical signal. According to one embodiment, the integrated optical linewidth reduction system further includes a ring/disk resonator disposed in the fourth optical path adapted to cause the longer propagation delay. According to one embodiment, the integrated optical linewidth reduction system further includes a waveguide grating disposed in the fourth optical path adapted to cause the longer propagation delay.

According to one embodiment, each of the first and second photo detectors is a photo diode. According to one embodiment, the first portion of the fourth optical signal is substantially equal to the first portion of the fifth optical signal. According to one embodiment, the first portion of the fourth optical signal is different from the first portion of the fifth optical signal. According to one embodiment, the second portion of the fourth optical signal is substantially equal to the second portion of the fifth optical signal.

According to one embodiment, the integrated optical linewidth reduction system further includes a phase wrapper adapted to generate the feedback control signal from the fourth electrical signal. According to one embodiment, the phase wrapper includes a phase rotator adapted to generate an in-phase signal and a quadrature-phase signal in response to the fourth electrical signal. The phase wrapper further includes an inverter adapted to perform a modulo operation on the in-phase and quadrature-phase signals.

According to one embodiment, the inverter includes a first mixer adapted to generate a first frequency converted signal in response to the in-phase signal and a first oscillating signal. The inverter further includes a second mixer adapted to generate a second frequency converted signal in response to the quadrature-phase signal and a second oscillating signal. The inverter further includes a first adder/subtractor adapted to subtract the second frequency converted signal from the first frequency converted signal, and a first counter adapted to count a number of transitions of the first adder/subtractor. The inverter further includes a second counter adapted to count a number of transitions of the second oscillating signal, and a second adder/subtractor adapted to subtract the second

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counter's count from the first counter's count to generate a difference representative of the phase noise of the first optical signal.

According to one embodiment, the integrated optical linewidth reduction system further includes a digital-to-analog converter adapted to convert an output signal of the second adder/subtractor to an analog signal. The integrated optical linewidth reduction system further includes a driver adapted to generate and apply the feedback control signal to the phase modulator in response to the analog signal.

According to one embodiment, the phase wrapper includes an integrator circuit adapted to integrate the fourth electrical signal to generate an integrated signal. The phase wrapper further includes a control circuit adapted to maintain the integrated signal between a first predetermined voltage and a second predetermined voltage by changing the integrated signal by a value associated with a phase shift of 2π in the phase modulator.

According to one embodiment, the integrator circuit includes an operational amplifier including an inverting input coupled to the fourth electrical signal. The integrator circuit includes a first capacitor having a first capacitance value coupled between the inverting input of the operational amplifier and an output of the operational amplifier. The control circuit includes a first comparator adapted to compare the integrated signal to the first predetermined voltage. The control circuit further includes a second comparator adapted to compare the integrated signal to the second predetermined voltage. The control circuit further includes a first switch adapted to charge a second capacitor to a third predetermined voltage. The first switch is further adapted to transfer a first charge from the second capacitor to the first capacitor thereby reducing the integrated signal by a value associated with a phase shift of 2π in the phase modulator when the first comparator detects the integrated signal is substantially equal to the first predetermined voltage. The control circuit further includes a second switch adapted to charge a third capacitor to a fourth predetermined voltage. The second switch is further adapted to transfer a second charge from the third capacitor to the first capacitor thereby increasing the integrated signal by a value associated with a phase shift of 2π in the phase modulator when the second comparator detects the integrated signal is substantially equal to the second predetermined voltage.

According to one embodiment of the present invention, a method of reducing linewidth of an incoming optical signal includes modulating the phase of the incoming optical signal in response to a feedback control signal defined by a first electrical signal, and generating a first optical signal travelling through a first optical path. The first electrical signal is representative of a phase noise of the first optical signal. An optical linewidth of the first optical signal is less than an optical linewidth of the incoming optical signal.

According to one embodiment, the method further includes splitting the first optical signal into at least second and third optical signals travelling through second and third optical paths. The method further includes splitting the third optical signal into at least fourth and fifth optical signals travelling through fourth and fifth optical paths and causing the fourth optical path to have a longer propagation delay than the fifth optical path. The method further includes generating a sixth optical signal by coupling a first portion of the fourth optical signal with a first portion of the fifth optical signal, and generating a seventh optical signal by coupling a second portion of the fourth optical signal with a second portion of the fifth optical signal. The method further includes generating a second electrical signal in response to the sixth optical

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signal, generating a third electrical signal in response to the seventh optical signal, and generating a fourth electrical signal in response to the second and third electrical signals, the fourth electrical signal being representative of a phase noise of the first optical signal.

A better understanding of the nature and advantages of the embodiments of the present invention may be gained with reference to the following detailed description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified block diagram of an integrated light source independent feedback linewidth reduction system, in accordance with one exemplary embodiment of the present invention.

FIG. 2 is a simplified block diagram of an integrated light source independent feedback linewidth reduction system, in accordance with another exemplary embodiment of the present invention.

FIGS. 3A-3F are simplified block diagrams of the phase/frequency noise detector shown in FIG. 2, in accordance with various exemplary embodiments of the present invention.

FIG. 4 is a block diagram of the phase wrapper shown in FIG. 2, in accordance with one exemplary embodiment of the present invention.

FIG. 5A is a block diagram of an integrating phase wrapper representing the phase wrapper shown in FIG. 2, in accordance with another exemplary embodiment of the present invention.

FIG. 5B is a representation of the voltage output versus time of the integrating phase wrapper shown in FIG. 5A.

DETAILED DESCRIPTION

FIG. 1 is a simplified block diagram of an integrated light source independent feedback linewidth reduction system 100, in accordance with one exemplary embodiment of the present invention. Light source independent feedback linewidth reduction system (alternatively referred to herein as linewidth reduction system) 100 is shown as including, in part, a splitter 104, an optical phase modulator 114, and a phase noise measurement block 124. Optical phase modulator 114 receives an incoming optical signal 115 from optical signal source 102 and is adapted to generate optical signal 134. Optical phase modulator 114, splitter 104, and phase noise measurement block 124 are coupled or connected in a feedback loop. Linewidth reduction system 100 is adapted to detect the phase noise of the optical signal 134 and subtract the detected phase noise from the phase of the received incoming optical signal 115 using negative feedback, thereby to deliver an optical signal 105 from splitter 104 that has a substantially reduced phase noise and linewidth than the received incoming optical signal 115. In the exemplary embodiment shown in FIG. 1, optical signal source 102 is shown as being a Laser and incoming optical signal 115 being a laser beam. It is understood, however, that optical source 102 may be any source generating an optical signal having a substantially high degree of coherence.

Optical signal source 102 is not part of the feedback loop in linewidth reduction system 100. Thus, the characteristics of optical signal source 102 do not affect the loop performance as in conventional linewidth reduction systems that may use feedback. For example, in conventional linewidth reduction systems the frequency modulation (FM) characteristics of a laser signal source may worsen the loop performance. Lin-

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ewidth reduction system **100** thus provides better linewidth reduction than conventional linewidth reduction systems with feedback.

In one embodiment, the various electrical and optical components/block of linewidth reduction system **100** may be integrated on the same substrate. In another embodiment, the various electrical components/block of linewidth reduction system **100** may be integrated on a first substrate, the various optical components/block of linewidth reduction system **100** may be integrated on a second substrate. In yet other embodiments, linewidth reduction system **100** may be formed on two or more substrates each having disposed thereon one or more electrical and one or more optical components.

For simplicity, the same reference number may be used to identify both the optical path through which an optical signal travels, as well as to the optical signal which travels through that path. For example, reference numeral **110** may refer to the optical path so identified in FIG. 1, or alternatively to the optical signal that travels through this path. Furthermore, in the following, the terms power divider, power splitter, Y-junction, coupler, or combiner are alternatively used to refer to an optical element adapted to split/divide a signal to generate more signals and/or couple/combine a multitude of optical signals to generate one or more signals. Such a component is also alternatively referred to herein as splitter/coupler.

Splitter/coupler **104** is adapted to split optical signal **134** from optical phase modulator **114** into two optical signals delivered to optical paths **105**, **110**. Accordingly, the two signals travelling through paths **105**, **110** may be defined as $e^{-j(\omega t + \phi(t))}$, with ω and $\phi(t)$ respectively representing the frequency and the phase noise of optical signal **134**. Optical signal **110** is coupled to phase noise measurement block **124**. Phase noise measurement block **124** is adapted to detect the phase or frequency noise of optical signals **134**, **110**, **105** and convert the detected phase or frequency noise (phase/frequency noise) of optical signals **134**, **110**, **105** to an electrical current or voltage signal, which then controls, in-part, optical phase modulator **114**.

Optical phase modulator **114** is adapted to modulate the phase of incoming optical signal **115** in response to a feedback control signal defined by the electrical current or voltage signal from phase noise measurement block **124**. The electrical current or voltage signal from phase noise measurement block **124**, representing the phase noise of optical signal **134**, is used to subtract the detected phase noise of optical signal **134** from the phase of the received incoming optical signal **115**, thus providing negative feedback. The negative feedback reduces the optical linewidth in optical signals **134**, **110**, **105** in relation to incoming optical signal **115**. Optical signal **105** is provided as the output of light source independent feedback linewidth reduction system **100** by splitter/coupler **104**.

FIG. 2 is a simplified block diagram of an integrated light source independent feedback linewidth reduction system **200**, in accordance with another exemplary embodiment of the present invention. Linewidth reduction system **200** is similar to and operates in the same manner as linewidth reduction system **100** except that linewidth reduction system **200** includes a phase/frequency noise detector **120**, a phase wrapper **130**, and a driver **112** together representing phase noise measurement block **124**.

Phase/frequency noise detector **120** is adapted to detect the phase or frequency noise of optical signals **134**, **110**, **105** via optical signal **110** and convert the detected phase or frequency noise (phase/frequency noise) of optical signal **110** to an electrical current or voltage signal. A number of different systems may be used to detect the phase or frequency noise of an optical signal, such as the Mach-Zehnder Interferometer

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(MZI) with unequal delay between the interferometer arms, multiple beam interferometers (e.g., Fiber Bragg Gratings), and Fabry-Perot resonators. If the detected signal contains the frequency noise information of the optical signal, it is integrated to provide the phase noise information. Phase wrapper **130** is adapted to wrap the detected phase by performing a modulo operation to generate a phase noise defined by $\phi_m(t) = \text{mod}(\phi(t), 2\pi)$. Driver **112** is adapted to amplify the output signal of phase wrapper **108**, which is representative of the phase noise of the optical signal **134**, and deliver the amplified signal to optical phase modulator **114**. Optical phase modulator **114** is adapted to modulate the phase of incoming optical signal **115** in accordance with the signal it receives from driver **112**. In other words, optical phase modulator **114** is adapted to subtract the detected phase noise from the phase of incoming optical signal **115**, and in response deliver an optical signal **134** that has a substantially reduced phase noise and linewidth.

FIG. 3A is a simplified block diagram of frequency/phase noise detector **120** shown in FIG. 2, in accordance with one embodiment of the present invention. Optical signal received from optical path **110** is split into two signals via splitter/coupler **202** and delivered to optical paths **155**, **160**. Disposed between optical paths **155** and **165** is a true-time delay element **212** adapted to delay the propagation time of the optical signal travelling from splitter/coupler **202** to splitter/coupler **204** via optical paths **155**, **165**.

Coupler **204** is adapted to couple the two optical signals it receives from paths **160**, **165** in accordance with a predefined ratio. For example, in one embodiment, such as the embodiment shown in FIG. 3A, splitter/coupler **204** couples 50% of the optical signal travelling through path **160** with 50% of the optical signal travelling through path **165** and delivers the coupled signal to photo detector **206** via path **170**. Coupler **204** couples the remaining 50% of the optical signal travelling through path **160** with the remaining 50% of the optical signal travelling through path **165** and delivers the coupled signal to photo detector **208** via path **180**. In another embodiment, splitter/coupler **204** may apply a different ratio to generate the optical signals it delivers to paths **170**, **180**. Photo-detectors **206**, **208** are disposed in a photo-detection circuit **210**.

As described above, a first component of the optical signal delivered to each of the photo detectors **206**, **208** is received from path **160**, and a second component of the optical signal delivered to each of the photo detectors **206**, **208** is received from path **165**. Since for each photo detector, the two components of the received optical signals have the same frequency, the current generated by each photo detector is substantially independent of the optical signal frequency. The current generated by each photo detector **206**, **208** is, however, substantially dependent on the difference between the phases of the two optical signals the phase detector receives. In other words, the current generated by each photo detector **206**, **208** is defined, in part, by the difference between the phases of the signals travelling through paths **160**, **165**. Consequently, the current generated by each photo detector **206**, **208** is representative, in part, of the frequency/phase noise of the optical signal **134** generated by optical phase modulator **114**. Furthermore, in accordance with embodiments of the present invention, because phase/frequency noise detector **120** includes a pair of photo detectors, noise-induced imbalances, such as laser intensity noise are coupled to both optical paths **170**, **180** and hence received in-phase by both photo detectors **206**, **208**, while the desired signal received by photo detectors **206**, **208** is out-of-phase. As a consequence, photo detection circuit **210**'s output current signal I_{out} defined by the difference between currents I_1 , and I_2 which flow respec-

tively through photo detectors **206**, **208**, has a substantially enhanced immunity to noise. Referring to FIGS. **2** and **3A**, current signal I_{out} generated by photo detection circuit **210** is delivered to phase wrapper **130**. A transimpedance amplifier (not shown) may be used to convert current I_{out} to a voltage and deliver this voltage to phase wrapper **130**.

FIG. **3B** is a simplified block diagram of another exemplary embodiment of frequency/phase noise detector **120** shown in FIG. **2**. The frequency/phase noise detector shown in FIG. **3B** is similar to the one shown in FIG. **3A** except that the frequency/phase noise detector of FIG. **3B** includes a resonator **220** disposed between delay paths **155**, **165** and a controller **225** adapted to vary the delay through resonator **220** in accordance with a sample of current signal I_{out} generated by phase detection circuit **210**.

FIG. **3C** is a simplified block diagram of another exemplary embodiment of frequency/phase noise detector **120** shown in FIG. **2**. The frequency/phase noise detector shown in FIG. **3C** is similar to the one shown in FIG. **3A** except that the frequency/phase noise detector of FIG. **3C** includes a ring/disk resonator **230** disposed between delay paths **155**, **165** to generate a delay. The optical signal in path **155** is received by the add port of ring/disk resonator **230**. The drop port of ring/disk resonator **230** delivers the optical signal to path **165**.

FIG. **3D** is a simplified block diagram of another exemplary embodiment of frequency/phase noise detector **120** shown in FIG. **2**. The frequency/phase noise detector shown in FIG. **3D** is similar to the one shown in FIG. **3A** except that the frequency/phase noise detector of FIG. **3D** includes a ring/disk resonator **235** disposed between delay paths **155**, **165** to generate a delay. The through ports of ring/disk resonator **235** are used to receive the optical signal from path **155** and deliver the optical signal to path **165**.

FIG. **3E** is a simplified block diagram of another exemplary embodiment of frequency/phase noise detector **120** shown in FIG. **2**. The frequency/phase noise detector shown in FIG. **3E** is similar to the one shown in FIG. **3A** except that the frequency/phase noise detector of FIG. **3E** includes a waveguide grating **240** disposed between delay paths **155**, **165** to generate a delay.

Frequency/phase noise detector **120** of FIG. **3A** has a wide-band frequency response due to its use of a true-time delay **212**. The frequency/phase noise detectors shown in FIGS. **3B-3E** have relatively narrower bandwidths. The bandwidths of the frequency/phase noise detectors shown in FIGS. **3B-3E** may be increased by using multiple cascaded (or coupled) resonators (Vernier effect realization) or tapered designs.

FIG. **3F** is a simplified block diagram of another exemplary embodiment of frequency/phase noise detector **120** shown in FIG. **2**, which includes a multitude of resonators coupled together to enhance the bandwidth of the resonator. Four such resonators **230₁**, **230₂**, **230₃**, and **230₄** are shown as being used in frequency/phase noise detector **120** of FIG. **3F**. Although it is understood that any number of such resonators may be coupled to one another to increase the bandwidth. It is also understood that resonators **230₁**, **230₂**, **230₃**, and **230₄** may have similar to different sizes.

FIG. **4** is a block diagram of phase wrapper **130** shown in FIG. **2**, in accordance with one embodiment of the present invention. Phase wrapper **130** is shown as including a phase rotator **330**, as well as a phase estimator **350** adapted to perform sine inversion. Phase estimator **350** (also referred to herein as Sine inverter) is shown as including first and second mixers **304**, **306**, an oscillator **308**, adders/subtractors **310**, **316**, counters **312**, **314**, and an optional digital-to-analog converter **318**.

Assume that the phase noise of the optical signal being detected is characterized by a Brownian motion. Accordingly, the variance of the optical phase noise increases linearly with time. In one embodiment, the input-output voltage across phase rotator **330** may be defined as:

$$V_{out}(t) = A \sin(k \int V_{in}(t)) \quad (1)$$

where A and k are constants. Phase rotator **330** may be formed using any number of known phase rotators to achieve phase rotation.

Sine inverter **350** is adapted to discriminate the phase-wrapped phase noise of the optical signal it receives from phase rotator **330**. The discriminated phase noise is subsequently subtracted from the phase of incoming optical signal **115** by phase modulator **114**, as shown in FIGS. **1**, **2**.

As is seen from FIG. **4**, mixers **304** and **306** of sine inverter **350** are adapted to down convert the frequency of the in-phase and quadrature-phase signal received from phase rotator **330** using RF source **308**. Adder/subtractor **310** is adapted to subtract the output signal of mixer **306** from the output of mixer **304** to generate a signal whose number of transitions or zero crossings are counted by counter **312**. Likewise, the number of zero-crossings of RF source **308** is counted by counter **314**. Adder/subtractor **316** subtracts the output of counter **314** from the output of counter **312** to generate a digital signal representative of the phase noise $\phi(t)$ of optical signals **134**, **110**, **105** (see FIGS. **1** and **2**). DAC **318** is adapted to convert the digital output signal of adder/subtractor **316** to an analog signal.

Assume that the input of the phase rotator is represented by

$$V_{in} x \frac{d\phi(t)}{dt},$$

with V_{in} representing a constant and $\phi(t)$ representing the phase noise of the incoming (input) signal, as described above. Accordingly, the output of adder/subtractor **310** may be represented as:

$$V_{out}(t) = A \sin(\omega_e t - K \phi_m(t)) \quad (2)$$

where K represents a constant, $\phi_m(t) = \text{mod}(\phi(t), 2\pi)$ represents the phase noise of optical signals **134**, **110**, **105** and ω_e represents the angular frequency of oscillator **308**. Accordingly, counter **312** generates a count defined by $(\omega_e t - K \phi_m(t))$, and counter **314** generates a count defined by $(\omega_e t)$. Consequently, the output of adder/subtractor **316** is a digital signal defined by $K \phi_m(t)$, which is representative of the phase noise of optical signals **134**, **110**, **105**. It is understood that any one of a number of known phase estimators that can estimate the phase ϕ from $\text{Sin}(\phi)$ or $\text{Cos}(\phi)$ may be used.

Referring to FIGS. **2** and **4** concurrently, the output of DAC **318** is further amplified by driver **112** and applied to optical phase modulator **114**. In response, optical phase modulator **114** subtracts the discriminated phase noise from the phase of the incoming optical signal **115**. The optical signal **134** supplied by optical phase modulator **114** thus has a substantially reduced phase noise and linewidth, a portion of which is split off by splitter/coupler **104** and provided as output of light source independent feedback linewidth reduction system **100**.

FIG. **5A** is a block diagram of an integrating phase wrapper **500** representing phase wrapper **130** shown in FIG. **2**, in accordance with another exemplary embodiment of the present invention. As described above, a transimpedance amplifier (not shown) may be used to convert the output current I_{out} from frequency/phase noise detector **120** to a

voltage, which is delivered to the phase wrapper 130 represented in FIG. 4. Alternatively, the output current I_{out} from frequency/phase noise detector 120 represented by current source 510 may drive integrating phase wrapper 500 without a transimpedance amplifier, as shown in FIG. 5A. The output current I_{out} from frequency/phase noise detector 120 provides the time derivative of the phase noise,

$$\frac{d\phi(t)}{dt},$$

and its integration provides the phase noise, $\phi(t)$, in optical signals 134, 110, 105.

Integrating phase wrapper 500 is shown as including an operational amplifier 515, comparators 520, 525, capacitors 530, 535, 540, and switches 545, 550, 555. Capacitor 540 and switch 555 are coupled across the negative input and output of operational amplifier 515 forming an integrator circuit adapted to integrate the output current I_{out} from frequency/phase noise detector 120 represented by current source 510 to generate an integrated signal, V_{out} , which provides the phase noise, $\phi(t)$, in optical signals 134, 110, 105.

FIG. 5B is a representation of the voltage output, V_{out} , versus time of the integrating phase wrapper shown in FIG. 5A. Referring to FIGS. 5A and 5B, initially switch 555 is closed which shorts the output of operational amplifier 515 to its negative input, which are both driven to the voltage applied to a positive input of operational amplifier 515, coupled to ground potential in this example. When switch 555 is opened at time=0, the integrator begins to integrate and integrated signal, V_{out} , begins to increase. As described above, the phase noise of the optical signal being detected may be characterized by a Brownian motion. Accordingly, the variance of the optical phase noise may continue to increase with time, resulting in the value of V_{out} potentially approaching the power supply rails for operational amplifier 515 and causing distortion in the phase noise signal.

Because the phase noise and its wrapped version between $-\pi$ and π has the same information, a control circuit may be adapted to maintain the integrated signal between predetermined voltages, V_S and $-V_S$, which are within the distortion free operating range of operational amplifier 515 and optical modulator 114, by performing the phase wrapping. The phase wrapping changes the integrated signal voltage by a predetermined voltage value of $2V_\pi$ associated with a phase shift of 2π radians in phase modulator 114, as explained in detail below. Accordingly, predetermined voltage V_S should be larger than predetermined voltage V_π .

Referring to FIGS. 5A and 5B, the control circuit includes comparators 520, 525, capacitors 530, 535, and switches 545, 550. Comparators 525, 520 are adapted to compare integrated signal, V_{out} , to predetermined voltages, V_S and $-V_S$, respectively. At time=0, switch 545 is adapted to charge capacitor 530 to a predetermined voltage, V_π . Switch 545 is further adapted to transfer the predetermined charge from capacitor 530 to capacitor 540, thereby reducing the integrated signal, V_{out} , by a value associated with a phase shift of 2π in the phase modulator, when comparator 525 detects integrated signal, V_{out} , is substantially equal to predetermined voltage, V_S . In one example, capacitor 530 is designed to have a capacitance value substantially equal to twice the capacitance value of capacitor 540, which causes a voltage shift in V_{out} of about $-2V_\pi$. It is understood that the choice of the ratio of capacitor 530 to capacitor 540 and the value of V_π is flexible as long as the desired reduction in the voltage of the integrated

signal, V_{out} , is by a value associated with a phase shift of 2π in the phase modulator. After transferring predetermined voltage, V_π , to capacitor 540, switch 545 is further adapted to recharge capacitor 530 to predetermined voltage, V_π .

Similarly, at time=0, switch 550 is adapted to charge capacitor 535 to a predetermined voltage, $-V_\pi$. Switch 550 is further adapted to transfer the predetermined charge from capacitor 535 to capacitor 540, thereby increasing the integrated signal, V_{out} , by a value associated with a phase shift of 2π (in the opposite direction compared to the example when charge is transferred from capacitor 530 to capacitor 540) in the phase modulator, when comparator 520 detects integrated signal, V_{out} , is substantially equal to predetermined voltage, $-V_S$. In one example, capacitor 535 is designed to have a capacitance value substantially equal to twice the capacitance value of capacitor 540, which causes a voltage shift in V_{out} by about $2V_\pi$. It is understood that the choice of the ratio of capacitor 535 to capacitor 540 and the value of $-V_\pi$ is flexible as long as the desired increase in the voltage of the integrated signal, V_{out} , is by a value associated with a phase shift of 2π in the phase modulator. After transferring predetermined voltage, $-V_\pi$, to capacitor 540, switch 550 is further adapted to recharge capacitor 533 to predetermined voltage, $-V_\pi$. Accordingly, while integrated signal, V_{out} , is within the predetermined range of voltages between V_S and $-V_S$, the integrated signal, V_{out} , is given by:

$$V_{out} = \frac{1}{C_1} \int_0^t i_{in} dt. \quad (3)$$

The above embodiments of the present invention are illustrative and not limiting. Various alternatives and equivalents are possible. Although, the invention has been described with reference to an optical signal source generating an incoming optical signal, which may respectively be a laser and laser beam by way of an example, it is understood that the invention is not limited by the laser or laser beam technology. Other additions, subtractions, or modifications are obvious in view of the present disclosure and are intended to fall within the scope of the appended claims.

What is claimed is:

1. An integrated optical linewidth reduction system comprising:

a phase modulator adapted to modulate the phase of an incoming optical signal in response to a feedback signal thereby to generate a first optical signal travelling through a first optical path, said feedback signal being a first electrical signal defined by the first optical signal, wherein an optical linewidth of the first optical signal is less than an optical linewidth of the incoming optical signal;

a first splitter/coupler adapted to split the first optical signal into at least second and third optical signals travelling through second and third optical paths said second optical path having a longer propagation delay than said third optical path;

a second splitter/coupler adapted to generate a fourth optical signal by coupling a first portion of the second optical signal with a first portion of the third optical signal and deliver the fourth optical signal to a fourth optical path, the second splitter/coupler being further adapted to generate a fifth optical signal by coupling a second portion of the second optical signal with a second portion of the third optical signal and deliver the fifth optical signal to a fifth optical path; and

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a photo detection circuit comprising first and second photo detectors, said first photo detector being adapted to generate a second electrical signal in response to the fourth optical signal, said second photo detector being adapted to generate a third electrical signal in response to the fifth optical signal, said photo detection circuit supplying a fourth electrical signal in response to the second and third electrical signals; said fourth electrical signal being representative of a phase noise of the first optical signal.

2. The integrated optical linewidth reduction system of claim 1 wherein said incoming optical signal is a laser beam.

3. The integrated optical linewidth reduction system of claim 1 further comprising:

- a delay element disposed in the second optical path adapted to cause the longer propagation delay.

4. The integrated optical linewidth reduction system of claim 1 further comprising:

- a resonator disposed in the second optical path adapted to cause the longer propagation delay; and
- a controller adapted to vary a delay associated with the resonator in accordance with a sample of the fourth electrical signal.

5. The integrated optical linewidth reduction system of claim 1 further comprising:

- a ring/disk resonator disposed in the second optical path adapted to cause the longer propagation delay.

6. The integrated optical linewidth reduction system of claim 1 further comprising:

- a waveguide grating disposed in the second optical path adapted to cause the longer propagation delay.

7. The integrated optical linewidth reduction system of claim 1 wherein each of said first and second photo detectors is a photo diode.

8. The integrated optical linewidth reduction system of claim 1 wherein said first portion of the second optical signal is substantially equal to the first portion of the third optical signal.

9. The integrated optical linewidth reduction system of claim 1 wherein said first portion of the second optical signal is different from the first portion of the third optical signal.

10. The integrated optical linewidth reduction system of claim 1 wherein said second portion of the second optical signal is substantially equal to the second portion of the third optical signal.

11. The integrated optical linewidth reduction system of claim 1 further comprising:

- a phase wrapper adapted to generate the feedback control signal from the fourth electrical signal.

12. The integrated optical linewidth reduction system of claim 11 wherein said phase wrapper comprises:

- a phase rotator adapted to generate an in-phase signal and a quadrature-phase signal in response to the fourth electrical signal; and
- an inverter adapted to perform a modulo operation on the in-phase and quadrature-phase signals.

13. The integrated optical linewidth reduction system of claim 12 wherein said inverter comprises:

- a first mixer adapted to generate a first frequency converted signal in response to the in-phase signal and a first oscillating signal;
- a second mixer adapted to generate a second frequency converted signal in response to the quadrature-phase signal and a second oscillating signal;
- a first adder/subtractor adapted to subtract the second frequency converted signal from the first frequency converted signal;

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- a first counter adapted to count a number of transitions of the first adder/subtractor;
- a second counter adapted to count a number of transitions of the second oscillating signal; and
- a second adder/subtractor adapted to subtract the second counter's count from the first counter's count to generate a difference representative of the phase noise of the first optical signal.

14. The integrated optical linewidth reduction system of claim 13 further comprising:

- a digital-to-analog converter adapted to convert an output signal of the second adder/subtractor to an analog signal; and
- a driver adapted to generate and apply the feedback control signal to the phase modulator in response to the analog signal.

15. The integrated optical linewidth reduction system of claim 11 wherein said phase wrapper comprises:

- an integrator circuit adapted to integrate the fourth electrical signal to generate an integrated signal; and
- a control circuit adapted to maintain the integrated signal between a first predetermined voltage and a second predetermined voltage by changing the integrated signal by a value associated with a phase shift of 2π in the phase modulator.

16. The integrated optical linewidth reduction system of claim 15 wherein said integrator circuit includes:

- an operational amplifier including an inverting input coupled to the fourth electrical signal; and
- a first capacitor having a first capacitance value coupled between the inverting input of the operational amplifier and an output of the operational amplifier,

wherein said control circuit includes:

- a first comparator adapted to compare the integrated signal to the first predetermined voltage;
- a second comparator adapted to compare the integrated signal to the second predetermined voltage;
- a first switch adapted to charge a second capacitor to a third predetermined voltage, the first switch further adapted to transfer a first charge from the second capacitor to the first capacitor thereby reducing the integrated signal by a value associated with a phase shift of 2π in the phase modulator when the first comparator detects the integrated signal is substantially equal to the first predetermined voltage; and
- a second switch adapted to charge a third capacitor to a fourth predetermined voltage, the second switch further adapted to transfer a second charge from the third capacitor to the first capacitor thereby increasing the integrated signal by a value associated with a phase shift of 2π in the phase modulator when the second comparator detects the integrated signal is substantially equal to the second predetermined voltage.

17. A method of reducing linewidth of an incoming optical signal, the method comprising:

- modulating the phase of the incoming optical signal in response to a feedback signal to generate a first optical signal travelling through a first optical path; and
- generating the feedback signal in accordance with the first optical signal, wherein said feedback signal is a first electrical signal, wherein an optical linewidth of the first optical signal is less than an optical linewidth of the incoming optical signal;
- splitting the first optical signal into at least second and third optical signals travelling through second and third optical paths;

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causing said second optical path to have a longer propagation delay than said third optical path;
 generating a fourth optical signal by coupling a first portion of the second optical signal with a first portion of the third optical signal;
 generating a fifth optical signal by coupling a second portion of the second optical signal with a second portion of the third optical signal;
 generating a second electrical signal in response to the fourth optical signal;
 generating a third electrical signal in response to the fifth optical signal; and
 generating a fourth electrical signal in response to the second and third electrical signals; said fourth electrical signal being representative of a phase noise of the first optical signal.

18. The method of claim 17 wherein said incoming optical signal is a laser beam.

19. The method of claim 17 further comprising:
 disposing a delay element in the second optical path to cause the longer propagation delay.

20. The method of claim 17 further comprising:
 disposing a resonator in the second optical path to cause the longer propagation delay; and
 varying a delay associated with the resonator in accordance with a sample of the fourth electrical signal.

21. The method of claim 17 further comprising:
 disposing a ring/disk resonator in the second optical path to cause the longer propagation delay.

22. The method of claim 17 further comprising:
 disposing a waveguide grating in the second optical path to cause the longer propagation delay.

23. The method of claim 17 wherein said first portion of the second optical signal is substantially equal to the first portion of the third optical signal.

24. The method of claim 17 wherein said first portion of the second optical signal is different from the first portion of the third optical signal.

25. The method of claim 17 wherein said second portion of the second optical signal is substantially equal to the second portion of the third optical signal.

26. The method of claim 17 further comprising:
 generating the second electrical signal in response to a first photo-detector; and
 generating the third electrical signal in response to a second photo-detector.

27. The method of claim 17 further comprising:
 generating an in-phase signal and a quadrature-phase signal in response to the fourth electrical signal; and
 performing a modulo operation on the in-phase and quadrature-phase signals.

28. The method of claim 27 further comprising:
 converting a frequency of the in-phase signal using a first oscillating signal;

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converting a frequency of the quadrature-phase signal using a second oscillating signal;
 subtracting the frequency converted quadrature-phase signal from the frequency converted in-phase signal to generate a first difference signal;
 counting a number of transitions of the first difference signal;
 counting a number of transitions of the second oscillating signal; and
 finding a difference between the number of transitions of the second oscillating signal and the number of transitions of the first difference signal, said difference being representative of the phase noise of the first optical signal.

29. The method of claim 28 further comprising:
 converting said difference to an analog signal; and
 modulating the phase of the incoming optical signal in accordance with the analog signal.

30. The method of claim 17 further comprising:
 integrating the fourth electrical signal to generate an integrated signal;
 maintaining the integrated signal between a first predetermined voltage and a second predetermined voltage by changing the integrated signal by a value associated with a phase shift of 2π in the phase modulator.

31. The method of claim 30 wherein said integrating includes:

providing an operational amplifier including an inverting input coupled to the fourth electrical signal; and
 coupling a first capacitor having a first capacitance value between the inverting input of the operational amplifier and an output of the operational amplifier,
 wherein said maintaining includes:

comparing the integrated signal to the first predetermined voltage;

comparing the integrated signal to the second predetermined voltage;

charging a second capacitor to a third predetermined voltage;

transferring a first charge from the second capacitor to the first capacitor thereby reducing the integrated signal by a value associated with a phase shift of 2π in the phase modulator when the integrated signal is substantially equal to the first predetermined voltage;

charging a third capacitor to a fourth predetermined voltage; and

transferring a second charge from the third capacitor to the first capacitor thereby increasing the integrated signal by a value associated with a phase shift of 2π in the phase modulator when the integrated signal is substantially equal to the second predetermined voltage.

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